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A LINEAR MODEL FOR OPTIMAL FUEL ALLOCATION

by

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ABSTRACT

A linear model for optimally allocating limited energy supplies is presented. The model is based on input-output data for the U.S. economy at the 90-sector level of detail. Results show that for substantial cutoffs of refined petroleum, the optimal allocation pattern to maximize GNP are quite similar to that for minimizing unemployment.

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1. INTRODUCTION

The Arab oil embargo of 1973-74 underscored the need for the development of effective contingency plans to allocate limited supplies of refined petroleum in a way that minimizes disruption of the economy. As a result, the Federal Energy Administration has developed an extensive monitoring program to produce baseline data from which future allocation plans could be derived.

The purpose of this report is to present and test a method for deriving an optimal allocation plan from such a set of baseline data. It is intended to provide qualitative information at an aggregated level indicating the sectors where economic activity could be reduced in ways that minimizes adverse effects on national product or employment.

The method assumes that objective functions to be maximized (e.g., GNP or total employment) can be expressed as linear functions of sector output levels. Linear programming techniques are used to optimize subject to linear constraints based on interindustry economic data from refs. [1,3]. The model is employed at the 90-sector level of aggregation, since fuel allocations among subsectors should probably be guided as much by climatological factors as by differences in processes and potential for conservation.

All data from this report are taken for the base year 1967 and the effects of a hypothetical "embargo" for that year are simulated. Our purpose here is only to present a method and discuss qualitative results. For quantitative relevance, updated information must be used.

To the extent that the relative energy (oil) intensities of commodities remain constant over time, we expect our qualitative observations to be relevant to the current situation.

2. GENERAL FORM OF CONSTRAINTS

With one exception, the control variables for this linear programming analysis consist of the gross domestic outputs of each of the 90 sectors of the CAC energy-employment model. The single exception is the output of electricity which has been split into that generated from coal, oil, gas, and from nuclear or hydroelectric plants. Thus, we have a total of 93 control variables.

One objective function for this application is GNP, expressed as a function of the control variables by taking the dot product with a vector of value added per unit output coefficients. Total employment can also be used as an objective function, expressed by dotting with a vector of coefficients of direct labor per unit output.

The constraints on the control variables are derived from two principal considerations. First of all, each variable is bounded above by capacity $X_i \leq \bar{X}_i$. The simple form of these constraints allows the IBM-MPSX linear programming package to handle them without including them in the constraint matrix. In addition, an upper bound has been imposed on the sum of coal-electricity and oil-electricity. This allows some establishments to switch from one mode to the other when one fuel is scarce.

The remaining constraints restrict the output of goods to final demand to an acceptable range. To handle such constraints we must express final demand in terms of the control variables. Let X be a 93 entry column vector representing the control variables. Let IM , FD ,

OUT and INT be 90 entry column vectors representing imported goods, goods to final demand, domestic output of goods and that portion of domestic output which is used up in domestic production, i.e. intermediate goods. Then we have the following relation:

$$IM + OUT = FD + INT$$

That is, the total amount of goods available are divided between final demand and use in domestic output.

We can rewrite the above as:

$$IM + \hat{I}^*X = FD + \hat{A}^*X$$

where $\hat{I}$ and $\hat{A}$ are 90 by 93 matrices of constants.

The matrix $\hat{I}$ is much like the identity matrix; it is all zero except that each row contains a unit element in the columns which represent domestic output of the row commodity. In this case only the electricity row contains more than one unit element; it has four unit elements in the four columns corresponding to the four modes of electric generation.

Similarly, the matrix $\hat{A}$ is analogous to the usual I/O technical matrix A. The entry in a given row and column represents the amount of the row commodity needed to produce one unit of the column activity. Except for the four electric columns, the columns of $\hat{A}$ are the same as the corresponding columns of A. Except in the three rows corresponding to coal, refined oil and gas the four electric columns are the same as the electric column of A. We have assumed that the twelve entries in these three rows and four columns are zero except for our estimates¹

¹Based on data from refs. [2,3].

of the amount of coal needed to generate one unit of coal generated electricity, the amount of oil per unit of oil-electricity and the amount of gas per unit of gas electricity.

Having obtained these coefficients we may now express our constraints on final demand as $\underline{FD} - IM_0 \leq (\hat{I} - \hat{A}) X \leq \overline{FD} - IM_0$ where $\underline{FD}$ and $\overline{FD}$ are lower and upper bounds on final demand and IM_0 is an exogenously determined vector of imports for the year under study.

3. PARAMETRIC ANALYSES

To determine the sensitivity of the economy to the level of imports of refined petroleum, two parametric analyses have been performed. For either of the two objective functions an optimal solution is obtained and then the refined petroleum entry of IM_0 is decreased by 10% increments until it becomes zero.

At each iteration the model adjusts itself to cope optimally with the decrease in refined petroleum imports. The model was formulated in such a way that such parametric analyses could be performed. This eliminated the need to repeat a complete dual simplex solution at each step.

The model was run twice, first solving for the optimal allocation of refined petroleum that would minimize the loss of GNP due to an embargo, the second to minimize unemployment. The problems are formulated below.

3.1 Problem Formulation

To maximize our objective function subject to tight constraints on all forms of energy and an explicit embargo on refined petroleum, we solved the following problem:

$$\max \sum_{i=1}^{93} b_i X_i$$

subject to

$$\underline{FD} - IM_0 \leq (\hat{I} - \hat{A})X < \overline{FD} - IM_0, \text{ and}$$

$$0 \leq X \leq 1.03 X_0 \quad \text{coal electric sector}$$

$$0 \leq X \leq X_0 \quad \text{other energy sectors}$$

$$X_{\text{coal-elec}} + X_{\text{oil-elec}} = (X_{\text{coal-elec}} + X_{\text{oil-elec}})_0$$

$$0 \leq X \leq 1.05 X_0 \quad \text{non-energy sectors}$$

The upper and lower bounds on final demands were taken to be 90% and 110% of nominal, respectively. Outputs of energy sectors are limited to their initial values, with slack for switching some oil fired electric generation to coal. Detailed information on input data is in the Appendix.

For the GNP objective function, the coefficients are given by

$$b_i = \frac{V_i}{X_i}$$

Where V_i is the value added by sector i and X_i is its base year domestic output.

For the employment objective function, the coefficients are simply the base year ratios of sector employment to output

$$b_i = \frac{L_i}{X_i}$$

In this problem data may be available for K different types of occupations B_{ki} : where

$$\sum_{k=1}^K B_{ki} = b_i.$$

This would provide information for a variety of additional constraints limiting inter-occupational mobility. One is tempted to seek regional

data and extend this concept, but this should await a careful error and sensitivity analysis. We expect the model to be most useful at the macro level.

3.2 Optimal Consumption Patterns

A comparison of the two parametric analyses reveals considerable similarity between the optimal economic configurations maximizing GNP on the one hand and labor on the other. As the quantity of imported refined petroleum is reduced in 10% steps, the contributions to final demand of the various sectors also tend to decline. Most often, the consumption of goods from a sector will drop from its upper limit to its lower limit in one step and remain there; what is remarkable is the parallel between this downward movement in the maximum GNP case and the movement in the maximum labor case. As a consequence, consumer conservation steps aimed at maintaining GNP are consistent with conservation measures to support employment.

Results are presented in Table 1. In the initial scenario where there is no reduction of refined oil imports, final demand in each sector is at its upper limit whether we use either GNP or labor as an objective. The first 10% reduction is accompanied by a decline in the consumption of refined petroleum whether we maximize either GNP or employment. Further reductions totaling 20%, 30% and 40% witness a continuation of this trend; refined petroleum consumption drops so that final goods from the other sectors of the economy can stay at their upper limits. Things finally begin to change when final demand for refined hits its lower limit in response to a 50% reduction in refined imports in the maximum

	SECTOR	GNP	LABOR
BEFORE 80%	Refined Petroleum	↓	↓
	Electricity	↓	↓
	Paving	↓	↓
	Asphalt	↓	↓
	Air Transportation	-	-
80%	Crude	↑	↓
	Livestock	↓	↑
	Agricultural Products	↓	↑
	Forestry & Fishery Prod.	↓	↑
	Iron Mining	↓	↓
	Nonferrous Metal Ores Mining	↓	↓
	Stone & Clay Mining	↓	↓
	Chemical & Fertilizer Mining	↓	↓
	Broad & Narrow Fabrics, Yarn and Thread Mills	↓	↓
	Misc. Textile Goods & Floor Coverings	↓	↓
	Paper & Allied Products	↓	↓
	Paperboard Containers	↓	↓
	Chemical Products	↓	↓
	Plastics	↓	↓
	Paints	↓	↓
	Rubber	-	↓
	Glass	↑	↓
	Stone & Clay	↓	↓
	Primary Iron & Steel Manufacturing	↓	↓
	Primary Nonferrous Metals Mfg.	↓	↓
	Metal Containers	↑	↓
	Other Fabricated Metal Products	↑	-
	Railroads & Related Services	↓	↓
	Highway Passenger Transportation	↓	↓
	Water Transportation	↓	↓
	Pipeline Transportation	↓	↓
	Water & Sanitary Services	↑	↓
	State & Local Government Enterprises	↑	↓
	Business Travel & Entertainment & Gifts	↓	↓
90%	New Construction	-	-
	Drugs, Cleaning & Toilet Prepara- tions	↑	↓
	Screw Machine Products, Bolts, Nuts, etc.	↑	↓
	Automobile Repair & Services	↑	↓
100%	Maintenance & Repair Construction	↓	↓
	Food & Kindred Products	↓	↓
	Tobacco	↑	↓
	Miscellaneous Fabricated Textile Products	↓	↑
	Lumber & Wood Products		
	Wooden Containers		
	Leather Tanning & Industrial Leather Products	↓	↓
	Motor Freight Transportation	↓	↓
	Real Estate	↑	↓
	Wholesale & Retail Trade	-	↑
	Hotels	↓	↑
	Federal Government Enterprises	↓	↑
	Office Supplies	↓	↑

Table 1. Summary of Results

Note: This table shows when consumption from a sector falls from its upper limits. The symbols are as follows:

- ↓ = Lower Limit
- = Basic or Intermediate Value
- ↑ = Upper Limit

When consumption from a sector falls from its upper limit for one of the objective functions, it generally goes to the lower limit on the following 10% cut in imports for both objective functions.

labor case while it occurs at the 60% reduction level for maximum GNP. With consumption of refined petroleum at a minimum it becomes important to conserve electricity; at the 60% import reduction level, electricity drops to its lower limit with the GNP objective function while in the labor analysis, consumption of electricity drops part way at 60% and hits bottom at 70%. Also at the 70% reduction level we see air transport dropping to a level between its upper and lower bounds; in the maximum labor case we see in addition that Paving and Asphalt drop to their lower bounds.

By far the most dramatic realignments occur when refined imports are reduced by 80%. Roughly a third of the sectors must fall to the lower limit of their final goods output if we seek to maximize either GNP or labor. An inspection of shadow pricing for these sectors reveals that conservation is most important in Refined Petroleum, Electricity, Paving and Asphalt, and to a lesser extent in Water and Air Transport, Chemical Mining, Chemical Products, Plastics and Nonferrous Metals. The 90% reduction level adds very little to these developments. The level of new construction going to final demand drops off under either objective function.² In the maximum GNP case Rubber and Metal Containers decrease to their minimums, while Drugs, Bolts and Nuts and Auto Repair drop in the maximum

² Although the model treats construction demand as an independent variable, it is closely linked to the rate of GNP growth, so this effect would be likely to occur as an immediate reaction to an embargo.. Similar effects would also be observed earlier in the automobile and travel related sectors (motels, recreational vehicles, tires, etc.) as a result of gasoline rationing.

labor case. The shadow prices here are not especially high and in general the optimal configurations at the 90% embargo level are much the same as at the 80% level.

The final reduction bringing refined imports to zero causes several more sectors to drop their final goods output to the lower limit. Again, these developments are minor; the very first sectors to drop out still have the largest shadow prices. One surprising development however is that two sectors have jumped back up to their upper limits after having gone to their lower limits. In the maximum GNP situation with no refined imports, the Nonferrous Metal and Chemical sectors are at their upper limits; only Nonferrous Metal has jumped in the labor analysis. Fortunately, the shadow prices indicating the value of further consumption in these sectors are small. Thus in an uncertain embargo situation it would probably be just as well to ration consumption in these areas since their conservation is relatively important at the lower levels of embargo.

3.3 Optimal Output Levels

As in the optimal consumption scenarios, the optimal output levels are much the same whether we use GNP or employment as an objective. Very little happens to the output levels of most sectors until imports of refined petroleum are reduced by at least 80%. In the range where imports are reduced from 10% to 50%, there is a 20% decrease in oil fueled electric production with a compensating increase in coal electric output. Conservation at the gasoline pumps has allowed the rest of the economy to remain at full strength. This position begins to decay noticeably at the 60% embargo level; oil electric output is cut in half and the output of several other sectors

stays at a relatively high level. The optimal allocation of oil to the 90 sectors of the economy is displayed in Table 2.

Table 2. Optimal Oil Allocation (expressed as percent of pre-embargo use)

SECTOR NAME	BEA SECTOR NUMBER	PERCENT OF NORMAL OIL ALLOCATION AT X% IMPORT CUTOFF		
		X=60%	X=80%	X=100%
1 COAL MINING	700	100.0(100.0)	100.0(100.0)	99.9(99.9)
2 CRUDE PETRO, GAS	800	100.0(100.0)	99.7(99.5)	98.9(98.9)
3 PETRO REFIN PROD	3101	100.0(100.0)	100.0(100.0)	100.0(100.0)
4 ELECTRIC UTIL	6801	53.8(53.8)	16.2(15.5)	0.0(0.0)
5 GAS UTILITIES	6802	100.0(100.0)	99.3(99.2)	97.7(97.6)
6 LIVESTOCK	100	100.0(100.0)	98.8(99.9)	90.8(90.4)
7 MISC AG PRODUCTS	200	100.0(100.0)	96.8(99.8)	91.6(90.7)
8 FOREST FISH PROD	300	100.0(100.0)	97.7(99.4)	89.1(89.7)
9 AG FOP, FISH SER	400	100.0(100.0)	98.1(99.8)	92.7(91.8)
10 IRON ORE MINING	500	100.0(100.0)	97.7(97.4)	93.0(92.8)
11 NONFERR MINING	600	100.0(100.0)	96.6(96.4)	93.2(92.9)
12 STONE CLAY MIN	900	100.0(100.0)	98.9(98.6)	91.7(91.1)
13 CHEM MINERAL MIN	1000	100.0(100.0)	95.0(95.1)	94.6(91.8)
14 NEW CONSTRUCTION	1100	100.0(100.0)	100.0(100.0)	90.0(90.0)
15 MAINT, REP CONST	1200	99.9(99.9)	99.3(96.6)	95.3(93.1)
16 ORDNANCE	1300	100.0(100.0)	100.0(100.0)	99.9(99.9)
17 FOOD	1400	100.0(100.0)	99.9(99.9)	90.4(90.3)
18 TOBACCO	1500	100.0(100.0)	100.0(100.0)	99.9(90.2)
19 FABRIC & MILLS	1600	100.0(100.0)	98.3(98.3)	96.6(97.7)
20 TEXTILE GOODS	1700	100.0(100.0)	94.9(94.9)	92.5(93.3)
21 APPAREL	1800	100.0(100.0)	100.0(99.9)	99.8(99.8)
22 FAB TEXTILE PROD	1900	100.0(100.0)	99.7(99.7)	93.0(99.1)
23 WOOD PRODUCTS	2000	100.0(100.0)	99.5(99.3)	92.0(92.8)
24 WOOD CONTAINERS	2100	100.0(100.0)	99.2(99.8)	94.1(94.5)
25 H'OLD FURNITURE	2200	100.0(100.0)	100.0(100.0)	99.2(99.2)
26 FURN, FIXTURES	2300	100.0(100.0)	100.0(99.9)	98.9(98.9)
27 PAPER PRODUCTS	2400	100.0(100.0)	97.3(97.3)	94.2(94.1)
28 PAPERBOARD CONT	2500	100.0(100.0)	99.1(99.0)	94.7(94.5)
29 PRINTING, PUBL	2600	100.0(100.0)	99.7(99.7)	97.7(97.5)
30 CHEM PRODUCTS	2700	100.0(100.0)	96.3(96.5)	93.8(93.3)
31 PLASTICS	2800	100.0(100.0)	97.2(96.9)	94.9(94.9)
32 DRUGS, TOIL PREP	2900	100.0(100.0)	99.8(99.8)	99.0(94.1)
33 PAINTS	3000	100.0(100.0)	98.8(97.9)	94.6(93.9)
34 PAVING	3102	100.0(100.0)	99.6(98.8)	91.8(91.1)
35 ASPHALT	3103	100.0(100.0)	99.3(97.9)	93.4(92.3)
36 RUBBER PROD	3200	100.0(100.0)	97.8(97.0)	94.6(94.5)
37 LEATHER PRODUCTS	3300	100.0(100.0)	99.9(99.9)	98.7(99.1)
38 FOOTWEAR	3400	100.0(100.0)	100.0(100.0)	99.4(99.8)
39 GLASS PRODUCTS	3500	100.0(100.0)	99.7(98.0)	95.4(95.1)
40 STONE CLAY PROD	3600	100.0(100.0)	99.2(99.0)	91.8(91.6)
41 PRIM YR, STL MANU	3700	100.0(100.0)	99.1(98.9)	96.1(96.0)
42 PRIM NONFER MET	3800	100.0(100.0)	98.7(98.5)	95.9(95.8)
43 METAL CONTAINERS	3900	100.0(100.0)	99.5(99.2)	92.5(92.1)
44 HEATING, PLUMBING	4000	100.0(100.0)	99.9(99.6)	92.8(92.6)
45 SCREW MACH PROD	4100	100.0(100.0)	99.8(99.8)	97.6(97.7)
46 FAB METAL PROD	4200	100.0(100.0)	99.6(98.9)	96.5(96.4)
47 ENGINES, TURBINES	4300	100.0(100.0)	99.8(99.8)	98.8(98.8)
48 FARM MACHINERY	4400	100.0(100.0)	99.8(99.9)	99.2(99.1)
49 CONST, MINING EQ	4500	100.0(100.0)	99.9(99.9)	99.1(99.0)
50 MAT HANDLING EQ	4600	100.0(100.0)	99.8(99.7)	97.4(97.2)
51 METALWORKING EQ	4700	100.0(100.0)	99.8(99.8)	98.9(98.8)
52 SPEC IND MACH	4800	100.0(100.0)	99.7(99.7)	99.1(98.9)
53 GEN IND MACH	4900	100.0(100.0)	99.6(99.6)	98.4(98.3)
54 MACH SHOP PROD	5000	100.0(100.0)	99.7(99.6)	97.7(97.6)
55 OFC, COMPUT MACH	5100	100.0(100.0)	100.0(100.0)	99.8(99.5)
56 SERVICE IND MACH	5200	100.0(100.0)	99.9(99.8)	97.9(97.8)

Table 2 (continued)

17	ELEC IND APPARAT	5300	100.0(100.0)	99.8(99.8)	98.5(98.5)
18	H'HD APPLIANCE	5400	100.0(100.0)	99.9(99.8)	99.0(99.0)
19	ELEC LIGHT EQ	5500	100.0(100.0)	99.8(99.6)	95.8(95.6)
20	R-TV COMMUN EQ	5600	100.0(100.0)	100.0(100.0)	99.8(99.7)
21	ELECTRONIC COMP	5700	100.0(100.0)	99.9(99.9)	99.2(99.5)
22	ELECTRICAL EQUIP	5800	100.0(100.0)	99.8(99.8)	98.3(98.2)
23	MOTOR VEH & EQ	5900	100.0(100.0)	100.0(100.0)	99.5(99.5)
24	AIRCRAFT & PARTS	6000	100.0(100.0)	99.9(99.9)	99.8(99.8)
25	TRANSPORT EQUIP	6100	100.0(100.0)	99.5(99.5)	99.3(99.3)
26	PROF SCIENT SUPP	6200	100.0(100.0)	99.9(99.8)	98.8(98.8)
27	OPTICAL SUPPLIES	6300	100.0(100.0)	99.9(99.9)	99.0(99.3)
28	MISC MANUFACT	6400	100.0(100.0)	99.8(99.8)	98.6(99.0)
29	RAILROAD	6501	99.9(99.9)	96.1(96.1)	93.2(92.8)
30	LOCAL TRANSPORT	6502	100.0(100.0)	92.7(92.7)	91.9(91.9)
31	MOTOR FGT TRANSP	6503	100.0(100.0)	99.5(99.5)	92.8(92.7)
32	WATER TRANSPORT	6504	100.0(100.0)	90.2(90.3)	88.9(88.8)
33	AIR TRANSPORT	6505	100.0(100.0)	94.4(94.4)	93.0(93.1)
34	PIPE LINE TRANSP	6506	100.0(100.0)	97.1(97.1)	96.6(96.6)
35	TRANSP SERVICES	6507	100.0(100.0)	96.7(96.7)	93.9(93.7)
36	COMMUNICATIONS	6600	100.0(100.0)	99.8(99.7)	98.5(98.4)
37	R-TV BROADCAST	6700	100.0(100.0)	99.6(99.6)	96.9(96.4)
38	WATER, SANIT SER	6803	100.0(100.0)	99.5(94.3)	93.1(92.9)
39	WHOLE, RETAIL TR	6900	100.0(100.0)	99.8(99.8)	98.0(98.6)
40	FINANCE INSUR	7000	100.0(100.0)	99.8(99.8)	98.8(98.3)
41	REAL ESTATE	7100	100.0(100.0)	99.8(99.8)	98.9(92.2)
42	HOTELS, PERS SER	7200	100.0(100.0)	99.9(99.9)	91.4(99.2)
43	BUSINESS SERVICE	7300	100.0(100.0)	99.6(99.6)	96.9(96.3)
44	AUTO REPAIR	7500	100.0(100.0)	99.8(99.8)	92.6(92.8)
45	AMUSEMENTS	7600	100.0(100.0)	99.9(99.9)	99.4(99.2)
46	MED, EDUC SER	7700	100.0(100.0)	100.0(100.0)	99.8(99.8)
47	FED GOVT ENTERP	7800	100.0(100.0)	99.7(99.7)	95.8(98.0)
48	ST, LOC GOVT ENT	7900	100.0(100.0)	99.2(95.4)	94.1(93.0)
49	BUSINESS, TRAVEL	8100	100.0(100.0)	99.5(99.5)	96.8(96.8)
50	OFFICE SUPPLIES	8200	100.0(100.0)	99.6(99.6)	96.2(97.8)

4. SUGGESTIONS FOR FUTURE WORK

Our purpose in presenting this method is to show the types of qualitative and quantitative results that can be obtained. If the appropriate data can be updated and put into a form compatible with the model, results relevant to the current situation may be obtained. At this point, however, we will discuss some of the obvious shortcomings of the model and suggest enhancements that might improve its applicability.

Underlying the model is the assumption that a sector's output is directly proportional to its oil input. To the extent that the industry can conserve (e.g. by adjusting thermostats and cutting back other consumption not required for their process), this assumption is too strong and will underestimate the conservation potential. Opportunities for fuel substitution will have the same effect. However, since the first oil embargo and subsequent increases in oil prices, many sectors have made step-function improvements in their efficiency of using oil (e.g. by insulating or plugging leaks) or have substituted away from oil to less expensive fuels. Therefore, we expect the situation to be "tighter" in a future embargo than it was in 1973. Energy input-output models are being developed and modified to account for fuel substitution possibilities and to separate process-related industrial heat demands from other requirements [4]. Once the extent of possible oil conservation by substitution is known, more sectors can be disaggregated in the same manner as electric utilities were in this work. With such a detailed specification, more can be done

with this linear programming technique than with constant-coefficient input-output results. The latter could have been used to replicate the work in this report, except for the ability to handle substitution in the electric utility sectors. (Cutbacks would follow the rank-ordering of energy and labor intensities.)

In a similar vein, the assumption implied about the dependence of employment on output levels may be improved. At the margin in a production cutback, the change in employment per unit output may be overestimated by our method. Qualitative results would probably be unchanged, however.

It may also be useful to combine a foreign trade model with this one to account for possible changes in the level and structure of U. S. trade during an extended embargo. The same malice precipitating an embargo might be directed toward destabilizing the international monetary market. To compensate for this, domestic outputs of U. S. firms may have to realign to such an extent that it may be difficult to base oil allocations on their previous use rates. Contingency import and export vectors derived from such analyses should be included in the constraints on final outputs.

Finally, the basic assumption of this model is that all final demands are independent. As noted earlier, certain elements are coupled (e.g. gasoline and tires) and this should be accounted for in a more detailed study based on more recent data. The model is useful for examining parametrically the effects of alternative gasoline rationing levels, etc. However, it should be noted that any final

demand constraints applied to a model such as this could only be expected to hold for a relatively short period of time, after which demand pressures could cause price changes sufficient to render the constant-coefficient approximations in the model invalid.

APPENDIX A: DATA SOURCES

Basic data for the matrix A are obtained from ref. [1], converted to physical units and a domestic base as described in ref. [5].

A.1 Objective Functions

Except for the electric sectors, the coefficients of the two objective functions are simply the 1967 ratios of value added [1] (or direct labor [6]) to gross domestic output [1]. In the absence of specialized data for the electric sectors, their labor per unit output coefficients have been assumed equal to the coefficient for electric generation as a whole.

Individualized value added per unit coefficients for the four electric sectors are obtained by selectively allocating input costs and output values to the appropriate types of generation. The non-energy inputs and value of output for electric generation are split among the four sectors in proportion to their contribution to total domestic generation measured in kilowatt hours. Energy inputs of coal, oil and gas are charged solely to the corresponding mode of generation, using average 1967 implied prices [1,3]. In this way a specialized value added can be obtained for each of the four electric sectors; dividing by the corresponding output yields the objective function coefficients.

A.2 Constraints

In the system of constraints, $\underline{FD} - IM_0 \leq (\hat{I} - \hat{A})X \leq \overline{FD} - IM_0$, $\underline{FD}$ and $\overline{FD}$ are taken to be 90% and 100% of base year final demand [1]. The vector IM_0 of imports represents the base year level of imports [1]. The upper bounds on capacity are assumed to be 105% of base year

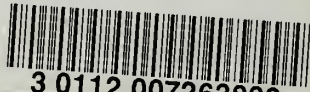
output levels except in the energy sectors where capacity is assumed to be equal to 1967 output. The single exception to this is the coal electric sector where capacity is set equal to 103% of historical output so that the model allows a shift from oil to coal generated electricity. The sum of coal and oil electric generation is constrained to the base year level.

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